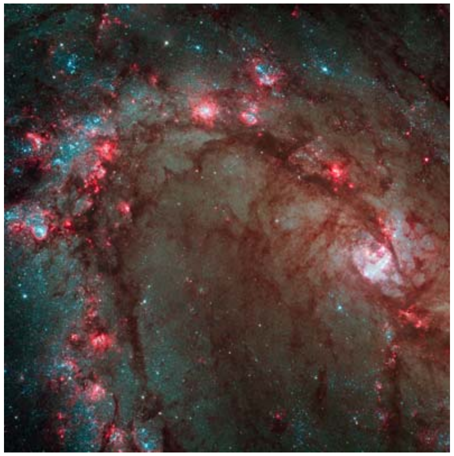
Star Formation Across Space

HST-ERS



Daniela Calzetti
(University of Massachusetts and
Stockholm University)

Legacy ExtraGalactic

LEGUS

Ultraviolet Survey

INAF – Osservatorio Astronomico di Bologna
Bologna, 17th May 2016

Legacy ExtraGalactic

Ultraviolet Survey

The LEGUS Team

Red for Senior Advisory Group
Blue for Science, Data Processing, EPO Leads

57 investigators (so far) at 30+ Institutions (US+EU+AU):

D. Calzetti (PI, UMass), J. Lee (Deputy PI, STScI), J. Andrews (U Arizona), A. Aloisi, S.N. Bright, T. Brown, C. Christian, K. Levay, M. Regan, E. Sabbi, L. Ubeda, B. Whitmore (STScI), A. Adamo, M. Messa, G. Östlin (Stockholm U), R. Chandar (Utoledo), **M. Cignoni** (UPisa), G. Clayton (LSU), D. Cook, D. Dale (U Wyoming), M. Krumholz (Mt. Stromlo), S. de Mink (Amsterdam U), C. Dobbs (UExeter), B. Elmegreen (IBM), D. Elmegreen (Vassar), A. Evans, K. Johnson (UVa), M. Fumagalli, G. Ashworth (U Durham), J. Gallagher, J. Ryon (UWisc), D. Gouliermis (MPIA), K. Grasha (UMass), E. Grebel, F. Shabani (Heidelberg U), A. Herrero, S. Taibi (IAC, Canarias), D. Hunter (Lowell Obs), L. Kahre, R. Walterbos (NMSU), R. Kennicutt (IoA, Cambridge), H. Kim (UT-Austin), D. Lennon (ESA), C. Martin, S. van Dyk (Caltech), P. Nair (U Alabama), A. Nota, L. Smith (STScI/ESA), A. Pellerin (SUNY-Geneseo), J. Prieto (UC de Chile), D. Schaerer (Geneva Obs), D. Schiminovich (Columbia U), D. Thilker (JHU), **M. Tosi**, **E. Sacchi** (INAF-UBologna), A. Wofford (IAP)

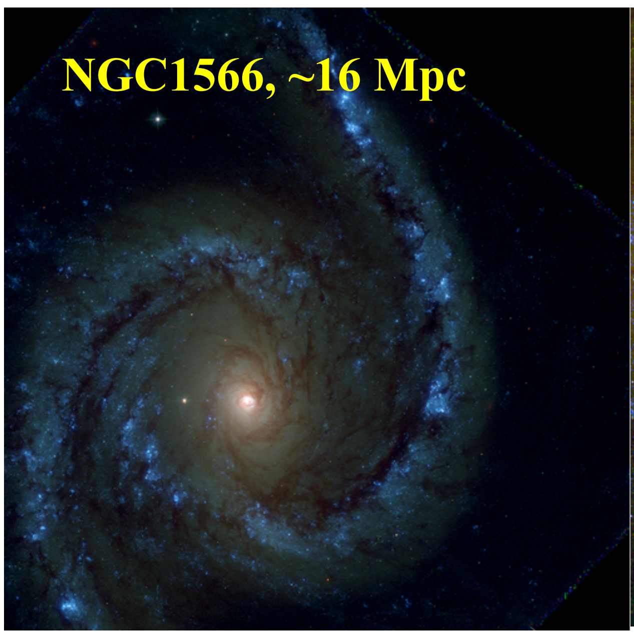
Legacy ExtraGalactic LEGUS Ultraviolet Survey

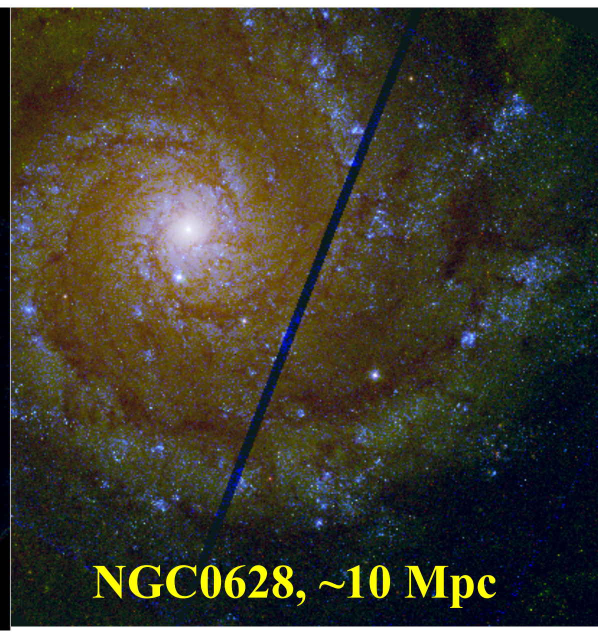
What Is LEGUS?

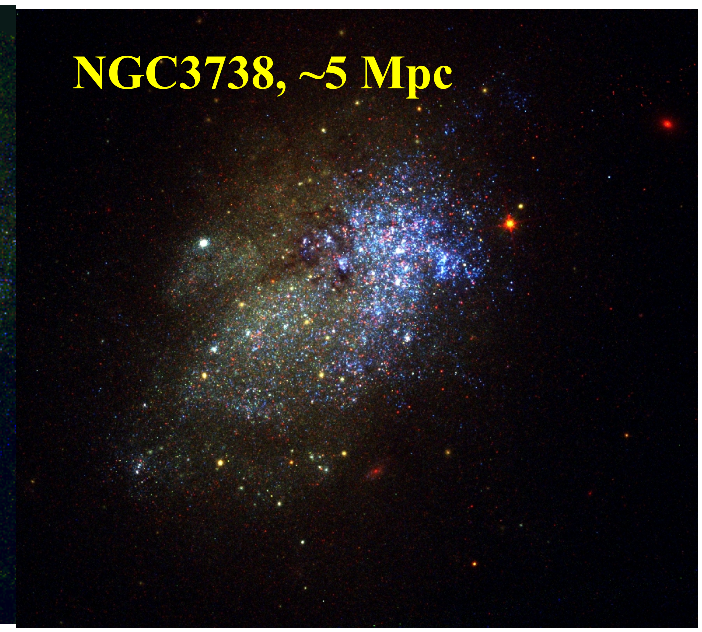
legus.stsci.edu C+2015

- Cycle 21 HST Treasury Program (154 primary + 154 parallel Orbits)
- 50 star-forming galaxies, in the range 3.5-12(15) Mpc, in 63 pointings; 100% complete as of Sept 2014.
- WFC3/NUV,U,B,V,I (5 bands) – leverage the HST Archive
- First public image release: 12 October 2015

https://archive.stsci.edu/prepds/legus/



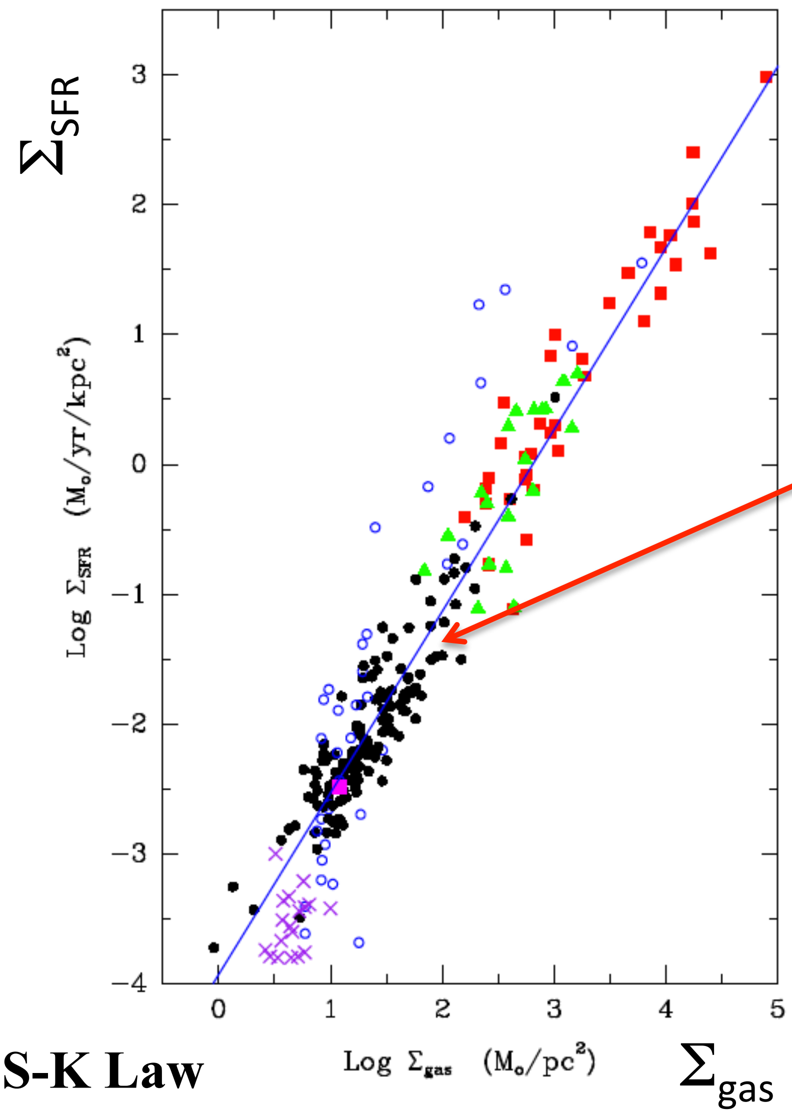




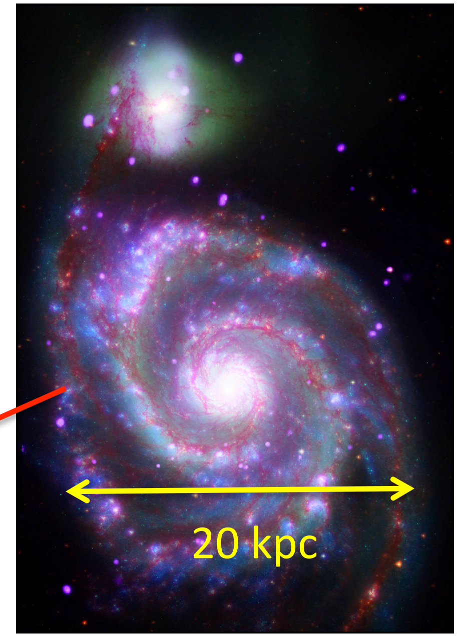
How Gas Converts to Stars …Within Galaxies

Σ = quantity/Area

Kennicutt & Evans, 2012



The S-K Law

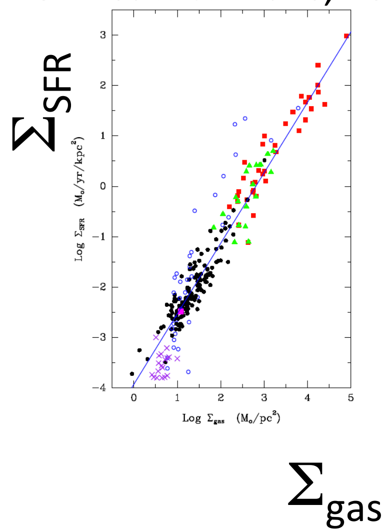


$$\Sigma_{SFR} \sim (\Sigma_{gas})^{\gamma}, \quad \gamma \sim 1.4$$

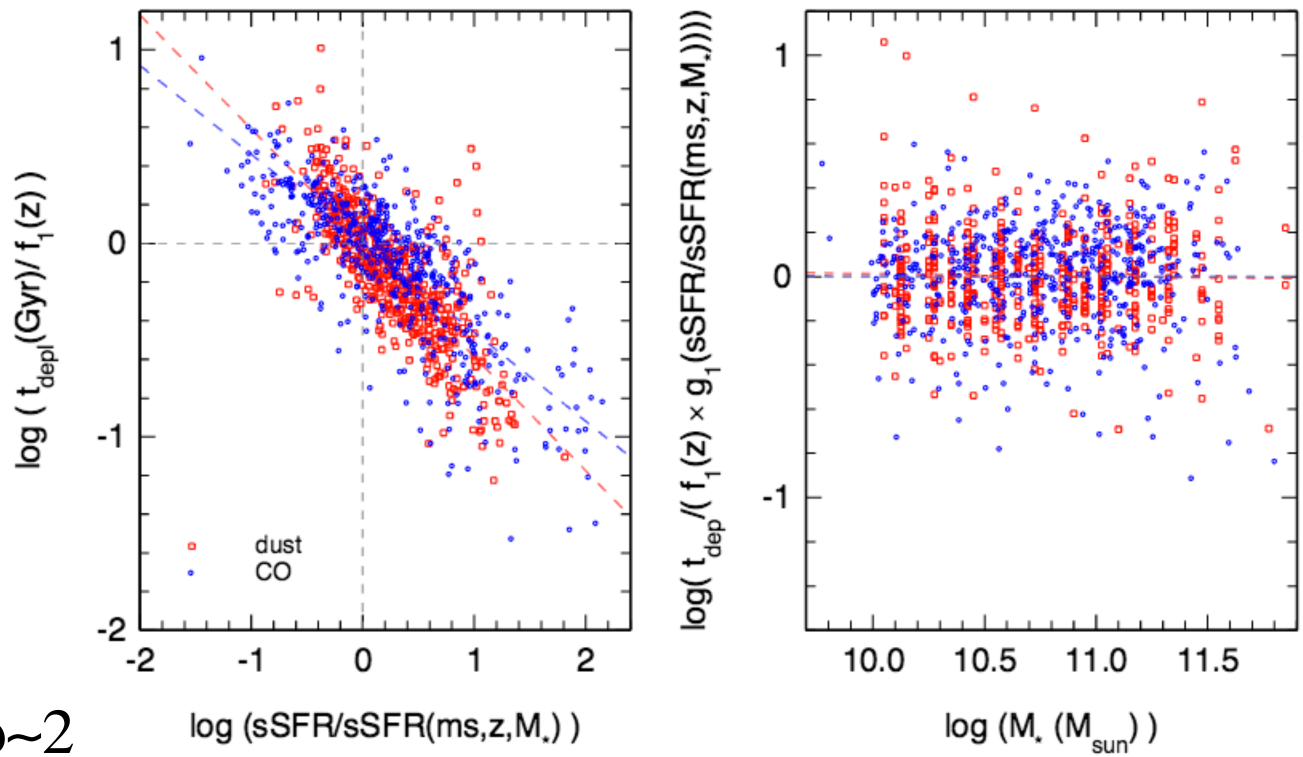
1. More active galaxies convert a larger fraction of their gas to stars. Why?
2. The star formation efficiency is low, ~1%-5%. Why?

…and as a Function of Redshift

Kennicutt & Evans, 2012



Genzel+2015, between z~0 and z~3



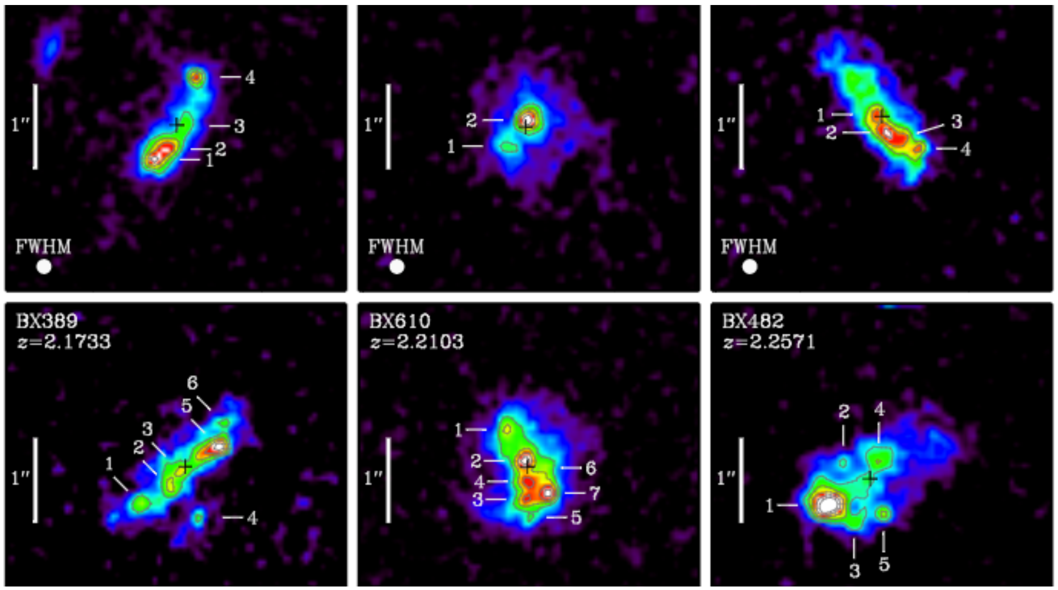
At Fixed Redshift:

$\mathrm{sSFR} \sim (f_{gas})^{\delta}$, $\delta \sim 2$

1. Also at high redshift, more active galaxies convert a larger fraction of their gas to stars. Why?
2. The star formation efficiency remains low. Why?

$\mathrm{sSFR} = \mathrm{SFR}/M_*$

Redshift Evolution of Star Formation



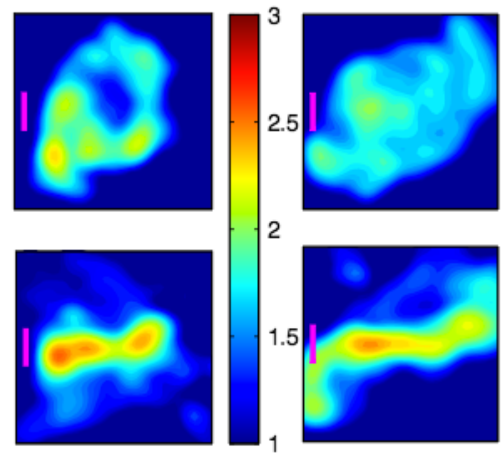
Forster-Schreiber+2011, z~2 disk galaxies

At z>~1, star formation occurs in giant, ~1 kpc size, 10^{8-9} M_o clumps.

Gravitational instabilities in gas rich disks? Help build the bulge via inward migration or in-situ SF?

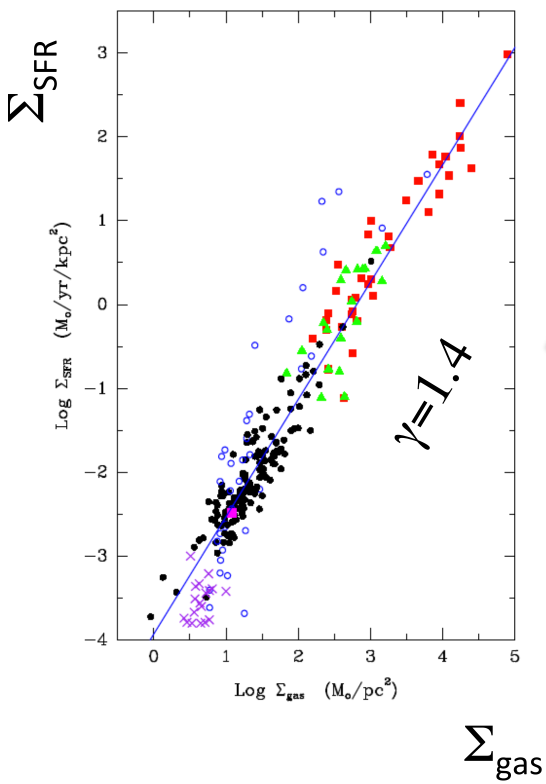
Nothing like this is observed in local galaxies, except in irregulars, with ~100-1000x lower clump masses (Elmegreen+2009)

The way galaxies form stars within their bodies has changed with time, and this process is still uncharted.



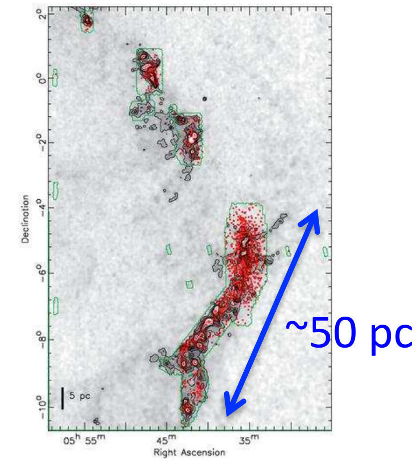
Hydro-simuls by Genel+2012

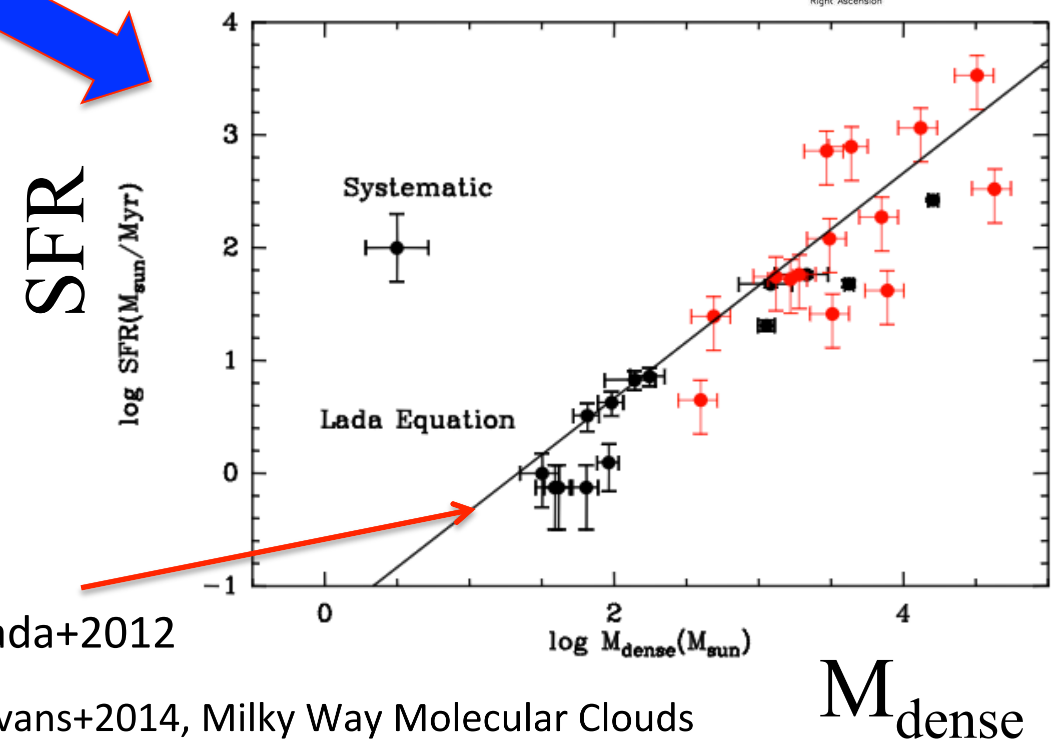
Star Formation: From Large to Small Scales



Kennicutt & Evans, 2012, Whole Galaxies

Orion Molecular Cloud, ~400 pc distance
Gutermuth+2011

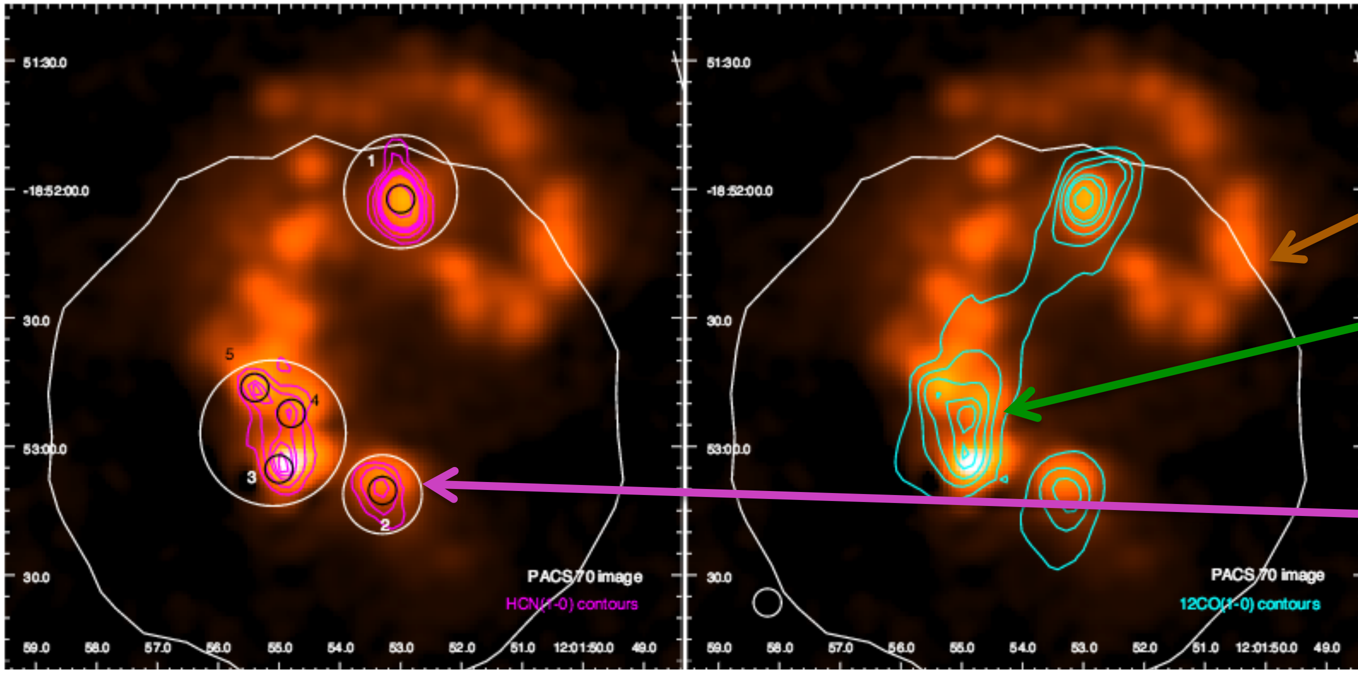




Model of Lada+2012

Evans+2014, Milky Way Molecular Clouds

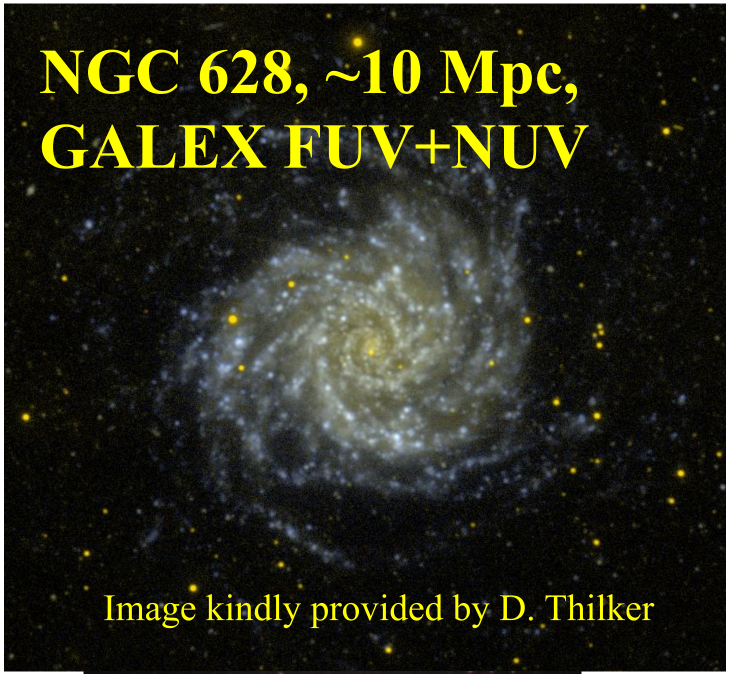
Gas or Star Formation?



Both gas and star formation require accurate characterization, **at all scales,** including the intermediate scales that link individual stars/star clusters to whole galaxies.

Physics: Star formation does not end with the formation of stars.
Technical: Molecular clouds and stars/star clusters resolved only up to 10-100 Mpc.

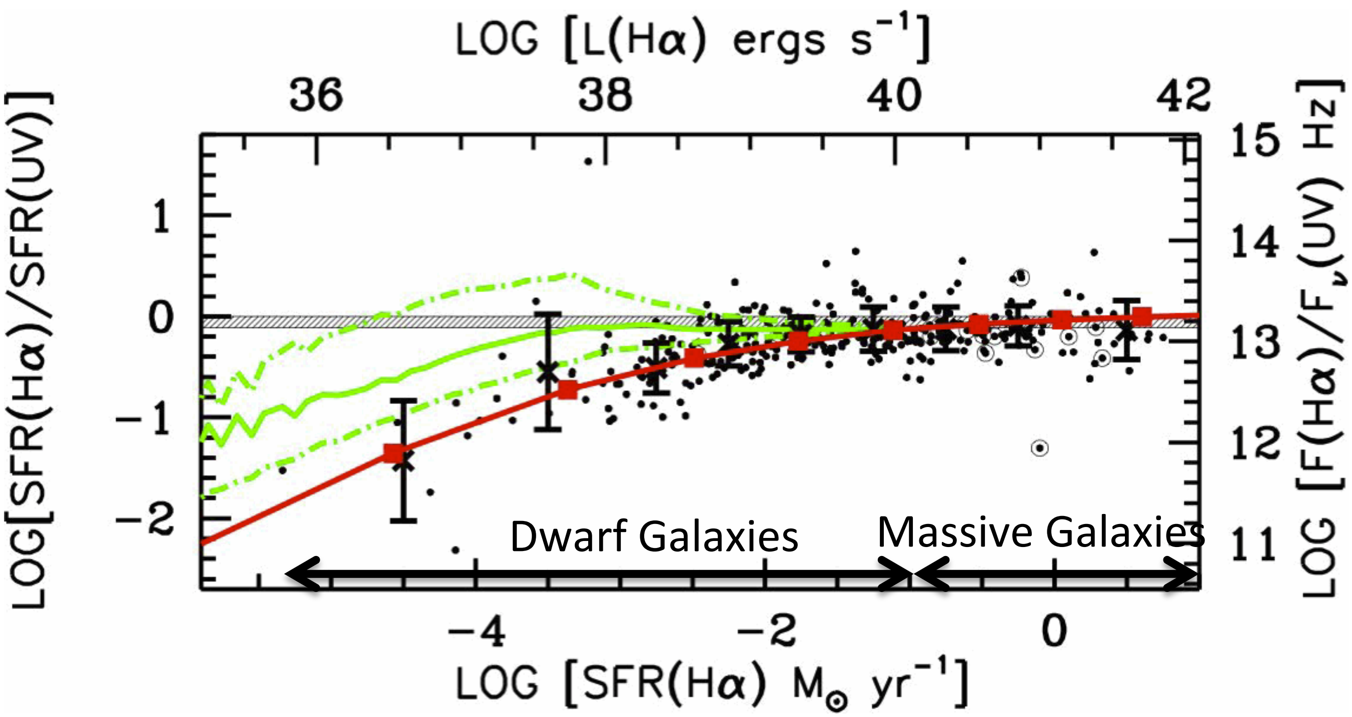
Star Formation Across `Space'



- How do stars form? Where? What is the role of the local environment?
- Do stars form with a universal stellar IMF?
- Do we have one or two (or multiple) modes of star formation (clustered and diffuse)? (Meurer et al. 1995, Crocker et al. 2014)
- What are the parameters that quantify the clustering? (Elmegreen et al. 2006)
- How do stellar structures evolve? On what timescale?
- How do bound structures (star clusters) form? How do they evolve? What are they tracing?
- How is the ISM powered by star formation?

How are measures of SFRs affected?

SFRs: UV vs Hα



Lee et al. 2009

UV from stars > 5 M_o (~100 Myr)

Hα from stars > 20 M_o (~7-8 Myr)

- Three potential (degenerate) causes:
  - Upper IMF variations (IMF)
  - Recent (<200 Myr) SFH decrease (τ)
  - Ionizing photon escape

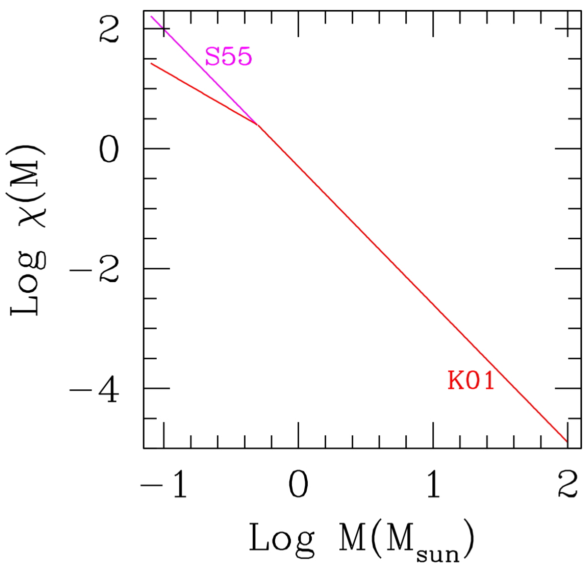
SFR Measures and The Stellar IMF

The Stellar Initial Mass Function is the distribution of stellar masses at birth. For Kroupa (2001, see also Chabrier 2003):

$$\begin{aligned} \chi(M) = dN/dM &= A\ M^{-1.3} & 0.1 \leq M(M_\odot) \leq 0.5, \\ &= 0.5\ A\ M^{-2.3} & 0.5 \leq M(M_\odot) \leq 120 \end{aligned}$$

Variations of the Upper-IMF crucially affect:

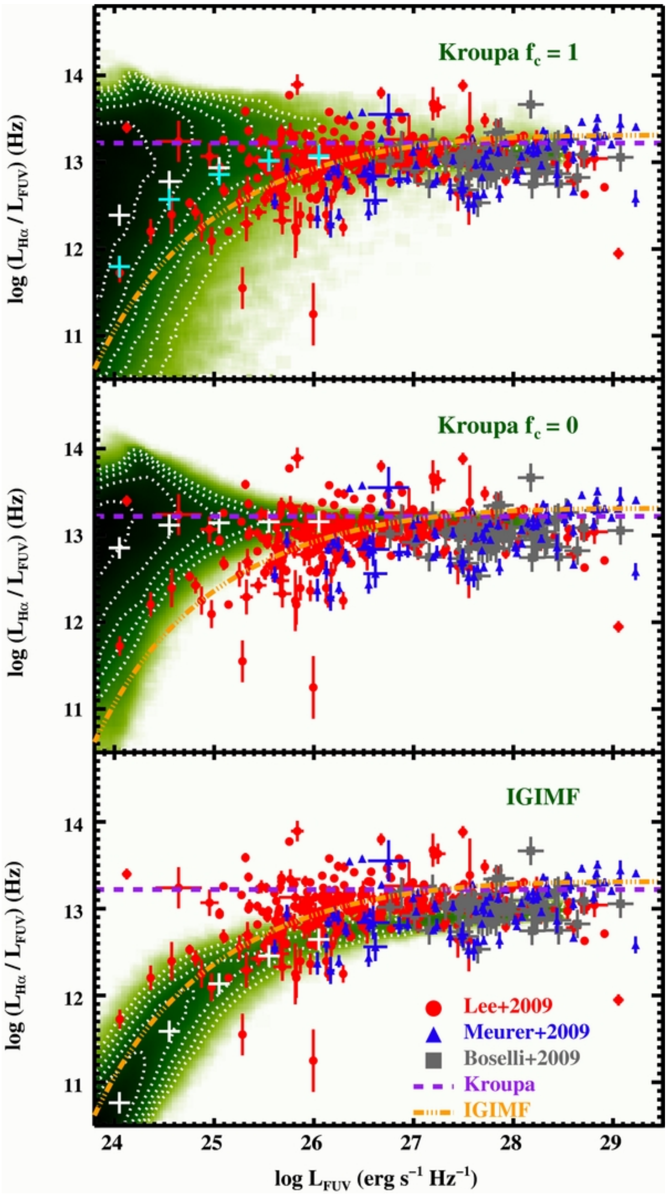
- SFRs at all cosmic distances
- Energy input into the ISM/IGM (feedback/ outflows)
- Metal enrichment/abundance ratios



Most current measures of Upper-IMF are for **massive, young** star clusters:

- In order to fully sample the Kroupa IMF, at least $2.7\ 10^5\ M_o$ in stellar mass need to be formed ($4.2\ 10^5$ stars!).

Tests on the Observed Variations



When stochastic sampling of the stellar IMF is included in the modeling of the Hα/UV ratio, the locus covered by the models is tantalizingly similar to that covered by the data.

The spread at low UV luminosities (~low mass galaxies) is due to the fact that not all model realizations contain massive stars.

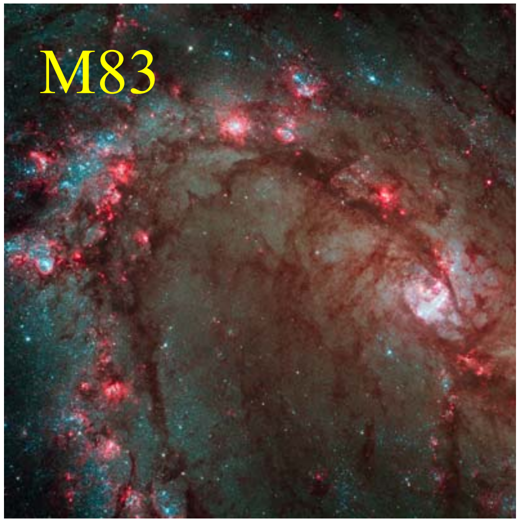
The complication of dealing with galaxies (which need to include their SFHs) makes the interpretation not completely satisfactory.

Move onto simpler systems than whole galaxies.

Fumagalli+2011

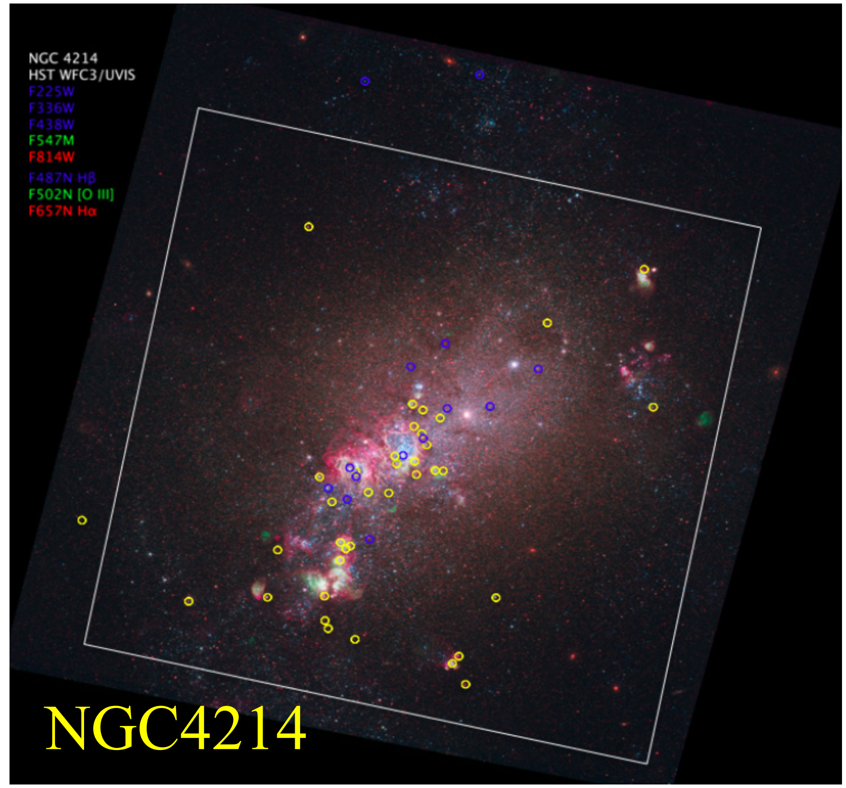
The Upper-IMF in Low-Mass Clusters

C.+2010, Andrews+ 2013, 2014



HST/WFC3
BB+NB
imaging

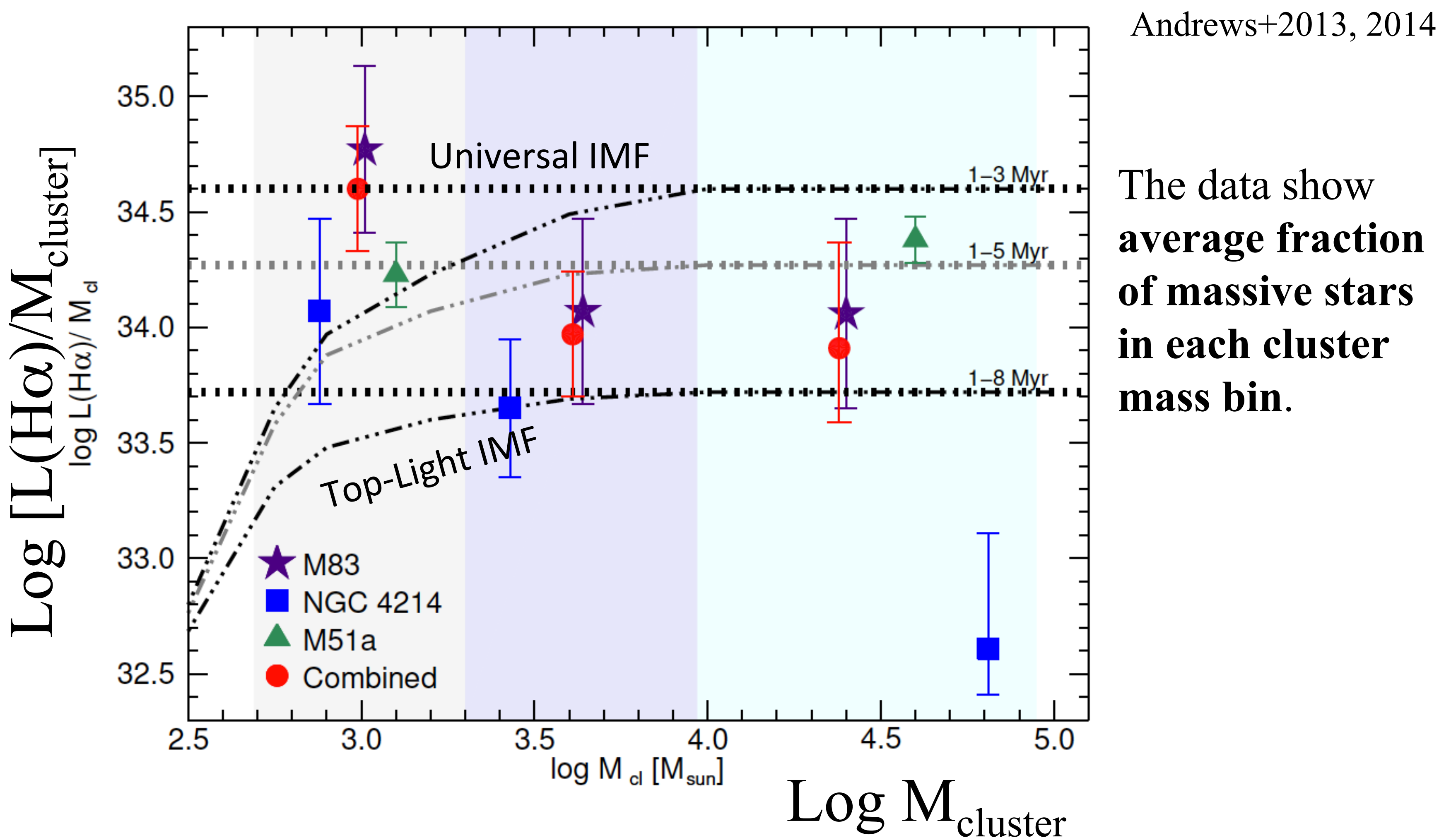
Young (for the massive stars) star clusters at a **range of masses** – enough numbers in each mass bin.



1. Ages and masses (using SED-fitting), to catalogue the clusters.
2. Extinction-corrected Hα (from NB) to measures the `fraction' of massive stars.

Star clusters are simpler systems than whole galaxies

Upper-IMF in Star Clusters



The data show **average fraction of massive stars in each cluster mass bin**.

A universal IMF is preferred at the 2-σ level only. Need to get tighter constraints using a larger number of star clusters in low density environments (e.g., dwarf galaxies).

The Open Questions

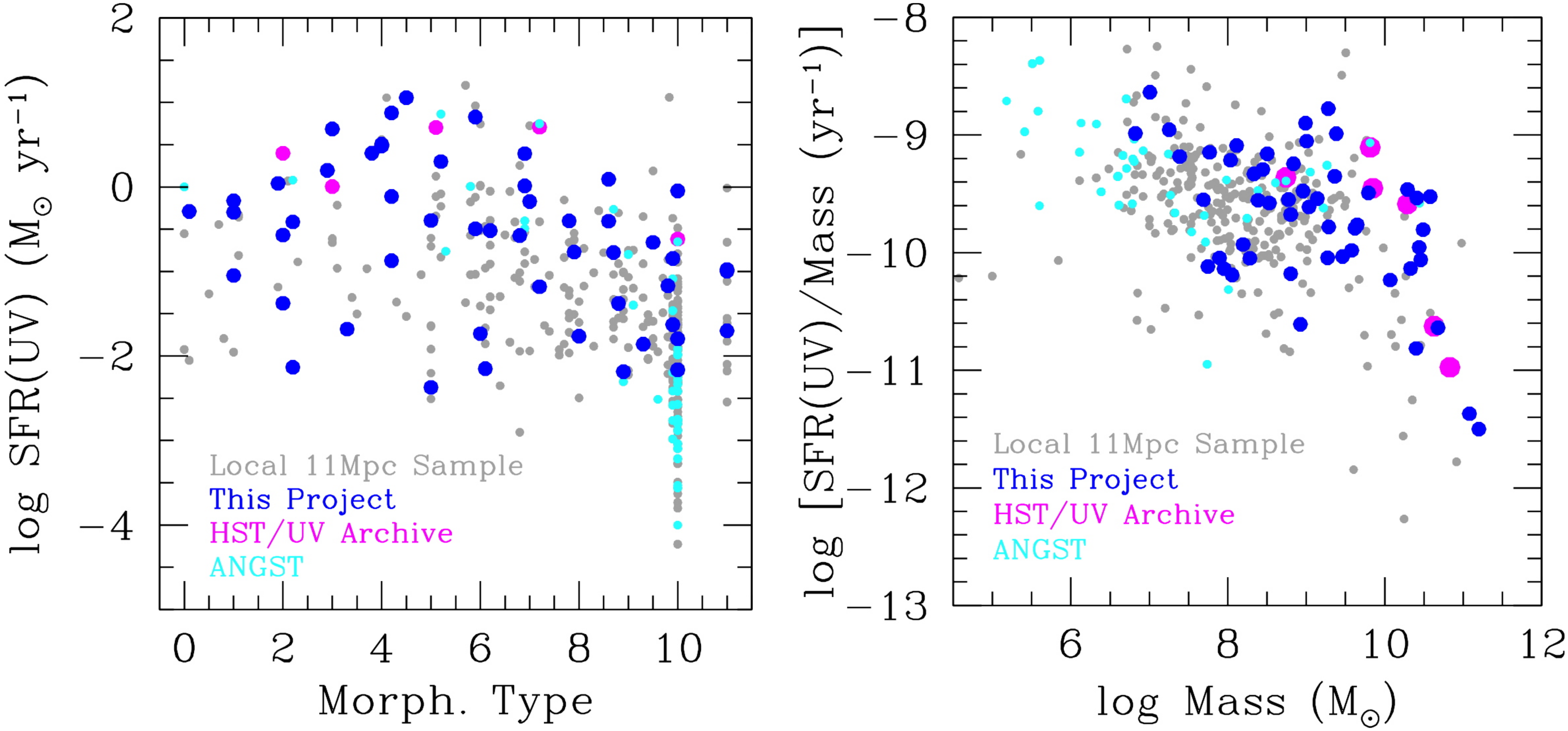
- The Physics of Galactic-Scale Star Formation
  - How Many Mode(s) of star formation
  - What are the Cluster-SF links (SFHs)
  - The Formation and Erasure of structures
  - The Links to dynamical structures, gas structures
  - Is this the route to reconcile SFRs?

- The Physical Underpinning of the IMF
  - Is the IMF truly Universal?
  - What are the driving parameters/mechanisms?

These are among LEGUS primary science goals

Legacy ExtraGalactic Ultraviolet Survey

The LEGUS Sample

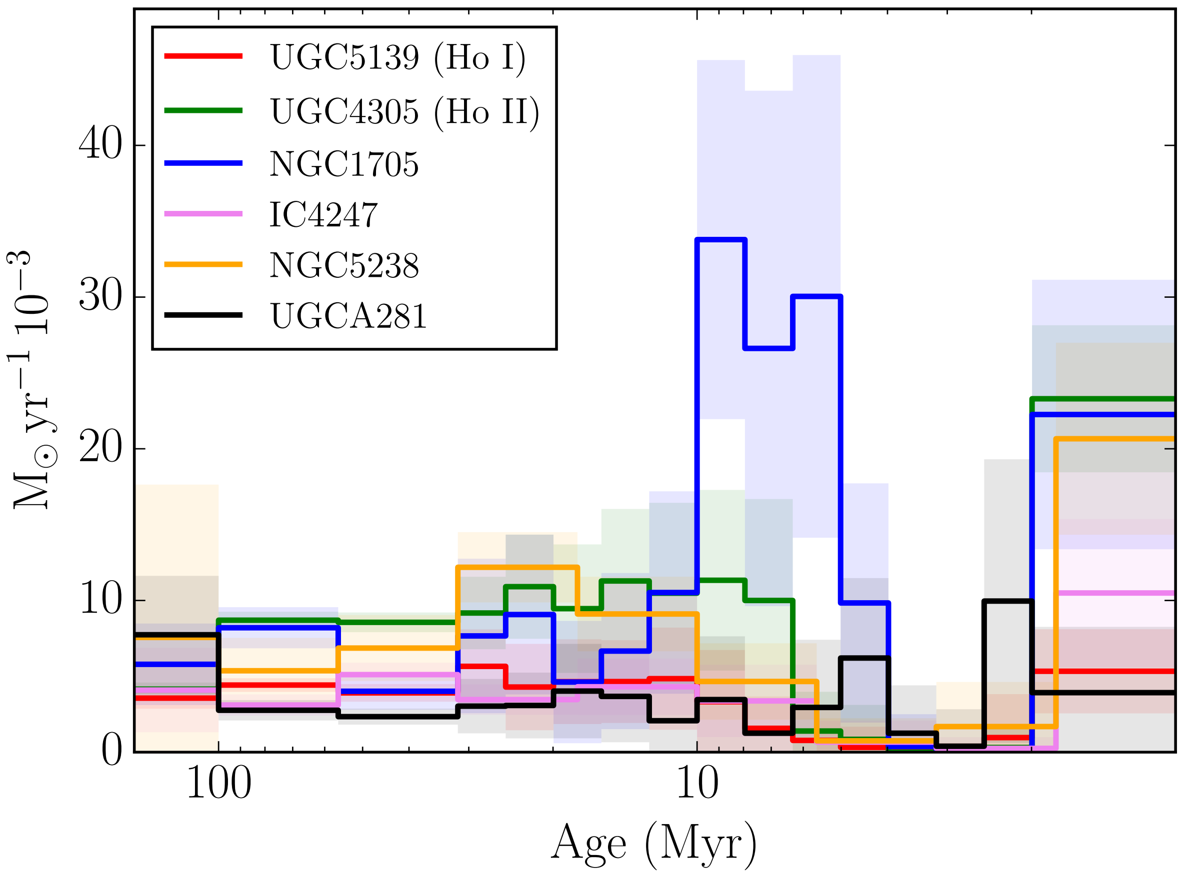


Full range of basic properties (morphology, sSFR, SFR, mass, interaction type, presence/ absence of bars, etc.) found in the local Universe, < 12-20 Mpc.

Produce catalogs of stars and star clusters, including their properties

Legacy ExtraGalactic Ultraviolet Survey

LEGUS SFHs (the first 6)

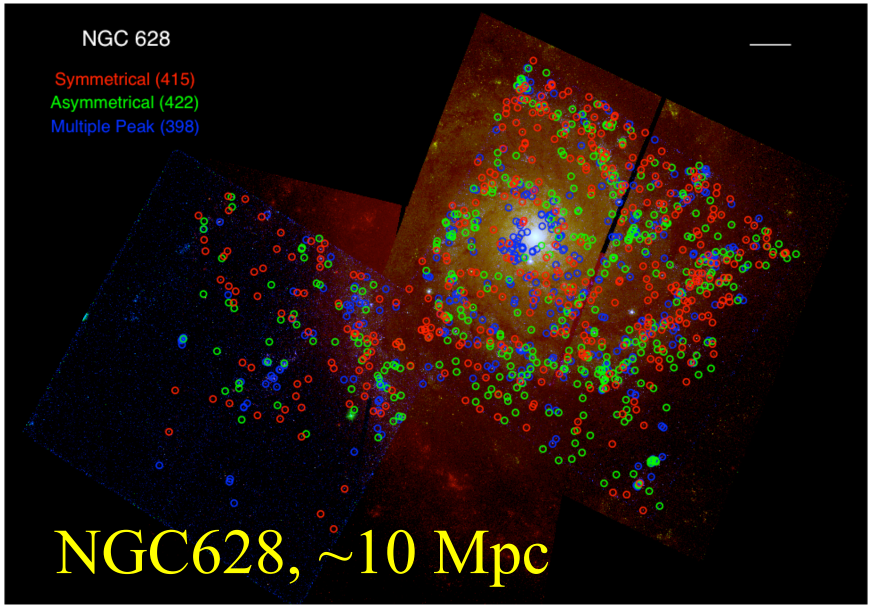


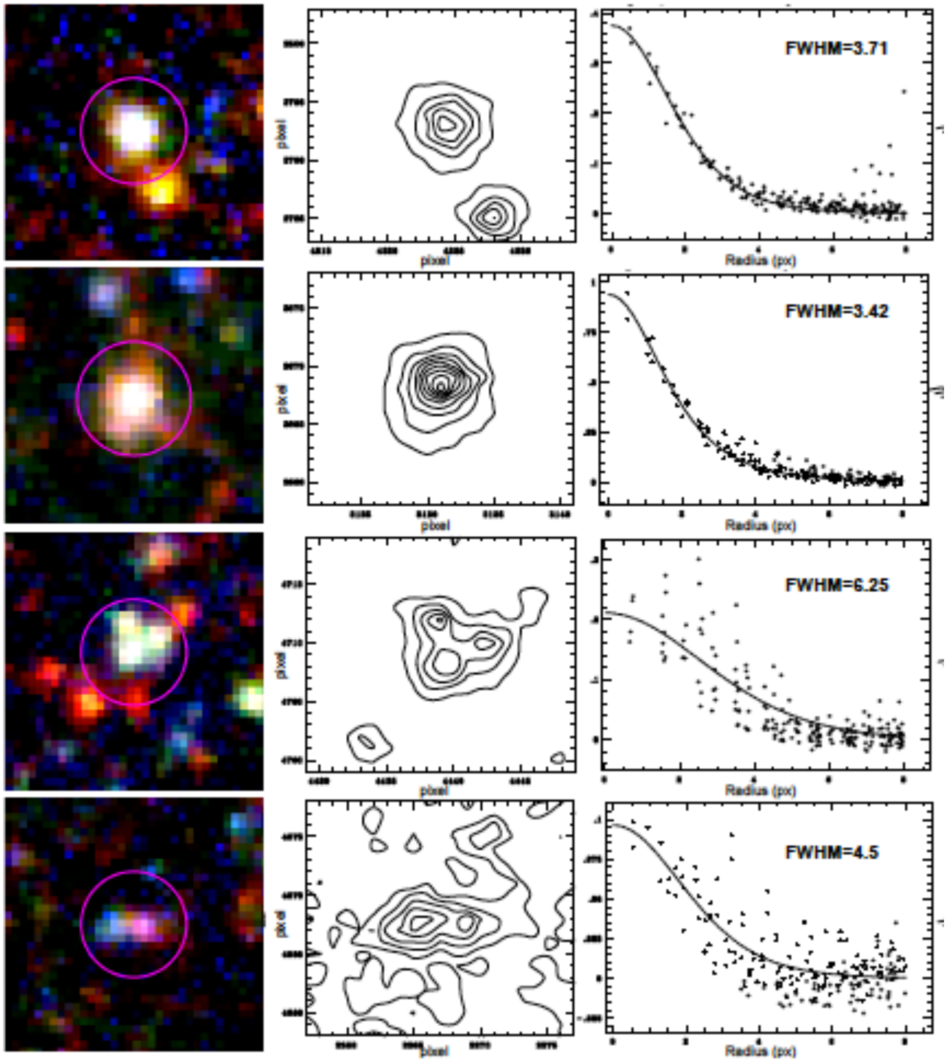
Investigated dwarf galaxies consistent with very low SFR over the past ~200 Myr (0.01 M_o/yr or about $1/10^{th}$ of the Magellanic Clouds). NGC1705 is an exception.

A by-product: the field IMF does not appear too different from Salpeter.

From U-V CMDs (Cignoni+2016)

Indentifying Star Clusters

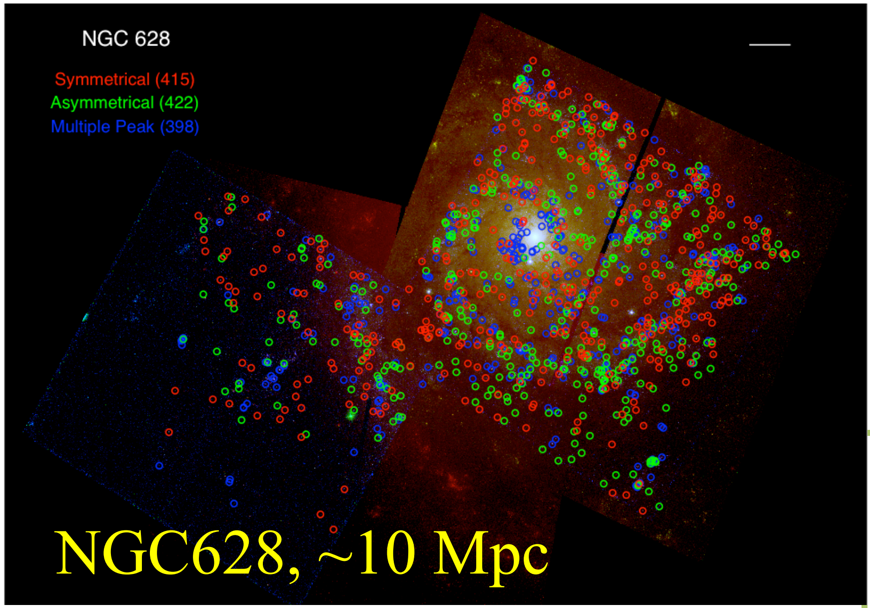




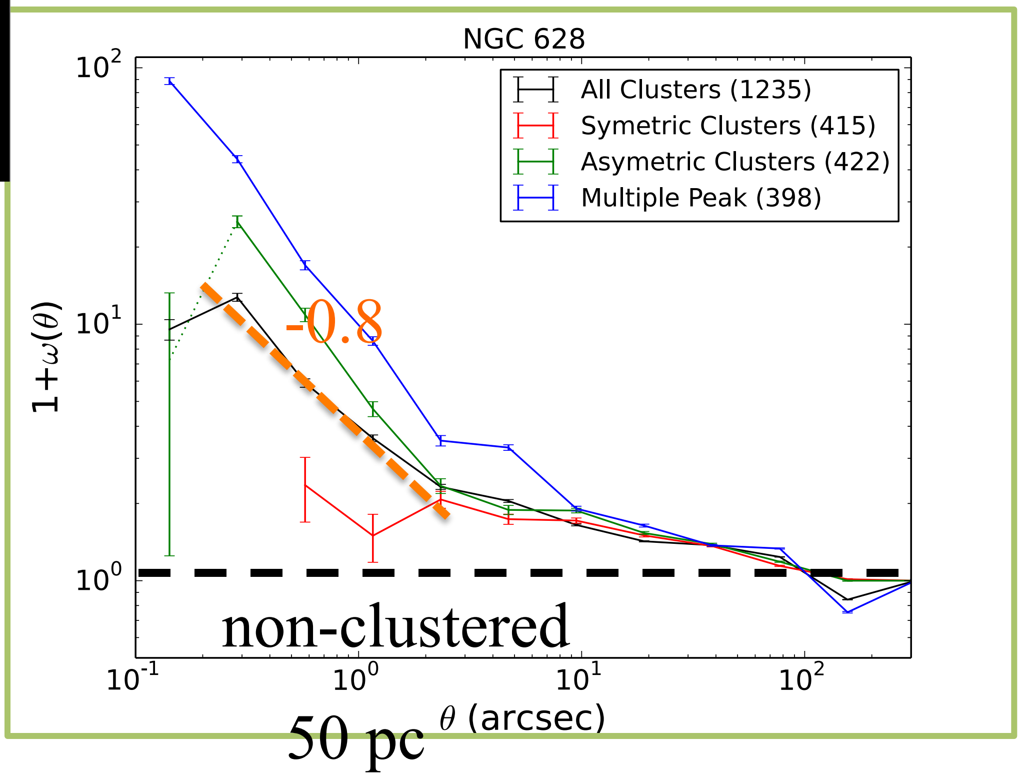
- Three classes:
  - Round, symmetric
  - Elongated
  - Multi-Peak

Adamo+2016

Clustering of Clusters



Analyze with 2-point correlation function:
The number of pairs that are above a random distribution at each separation R(pc) or Θ(arcsec).

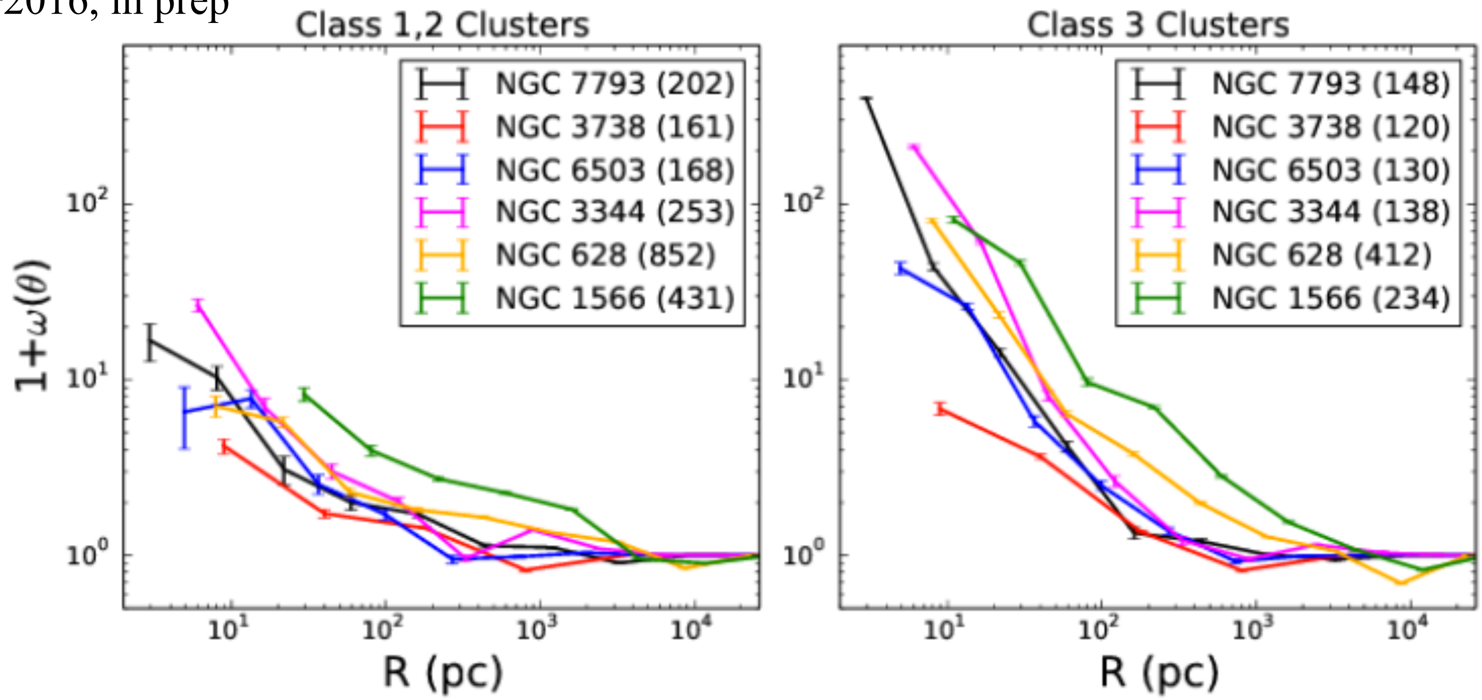


- Cluster randomization timescale at ~ 40 Myr in NGC628
- Mostly due to dissolution of young star clusters/associations
- Clustering disappears beyond ~150 pc

Grasha+2015, ApJ

Clustering of Clusters - 2

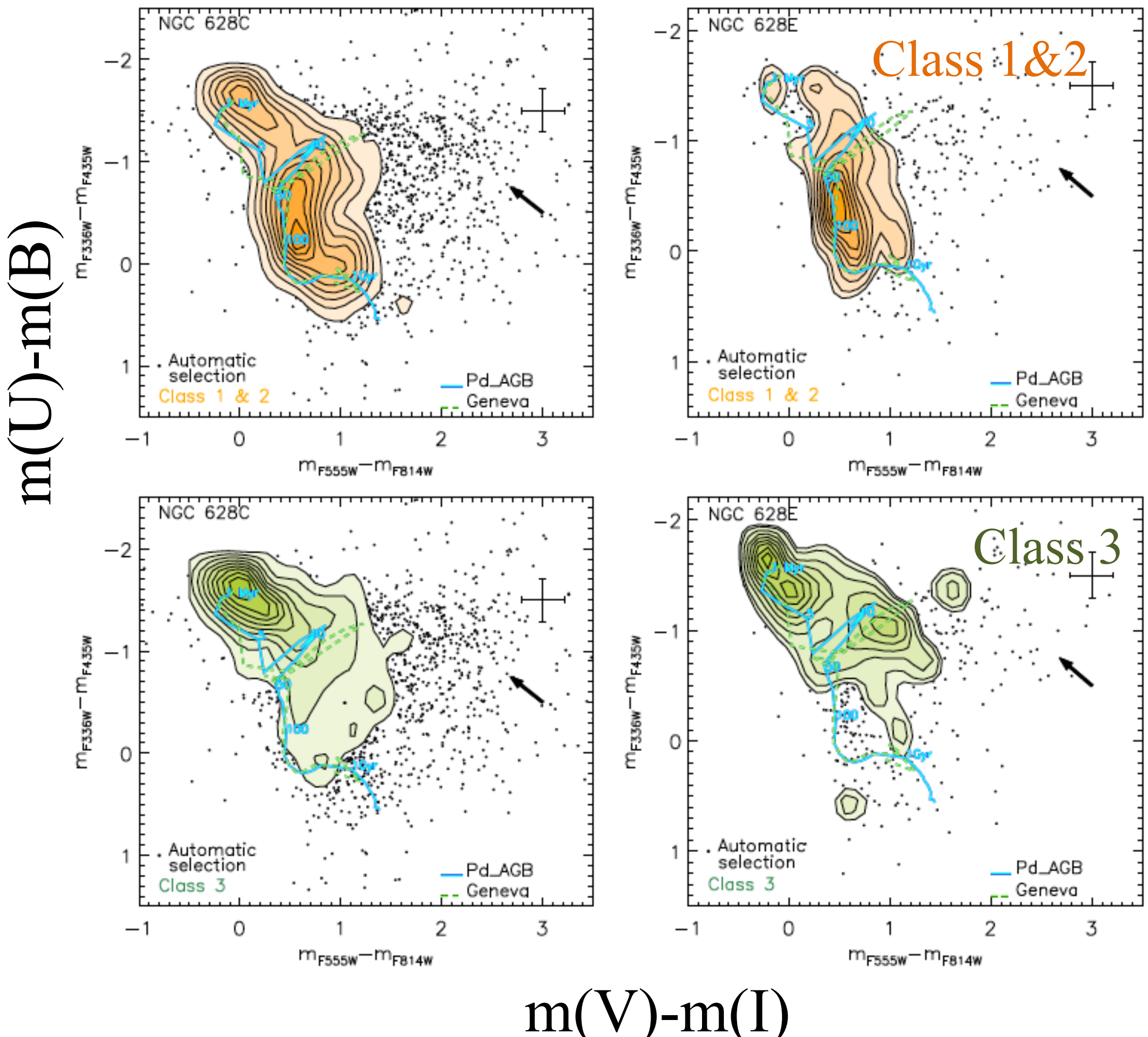
Grasha+2016, in prep



- Over several galaxies, the results are similar to those of NGC628:
  - Class 3 is significantly more clustered than the other two classes (-0.5:-1.5 vs. -0.3:-0.8), and typically younger.
  - Clustering of clusters disappears after a few tens of Myr. Most likely an effect of dissolution of the young component.
  - Clustering is only detectable out to ~200-300 pc (preliminary).

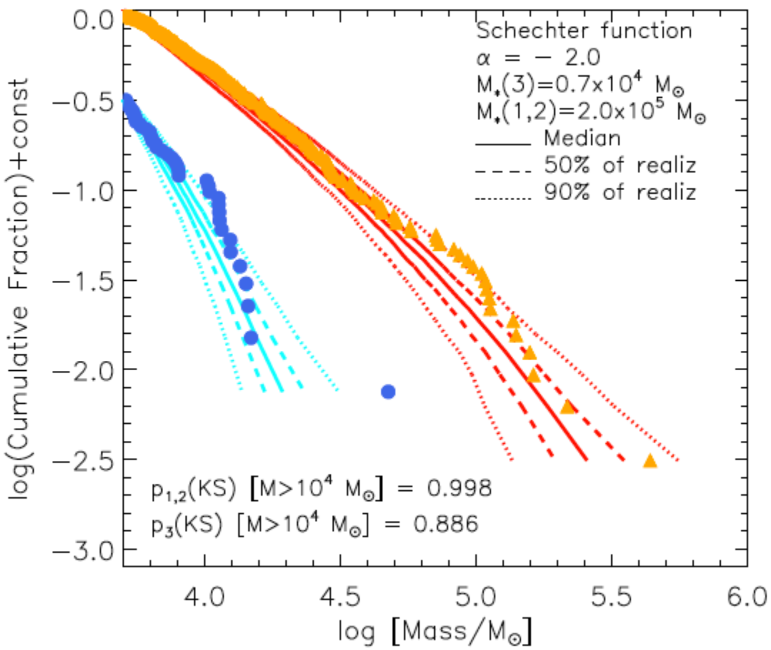
Properties of Star Clusters

- In NGC0628, Class 1+2 clusters cover a wider range of ages (~0-200 Myr) than Class 3 clusters (~0-50 Myr)
- They are also more massive, as derived from deterministic models, which include nebular emission and a fixed IMF.

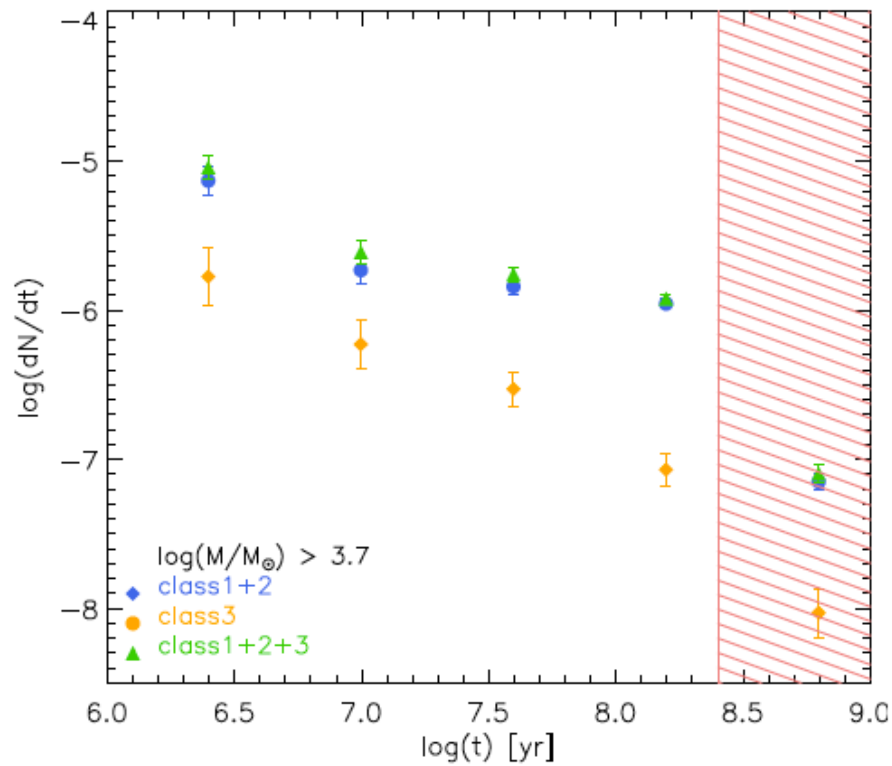


Adamo+2016

Evolution of Star Clusters



- Class 1+2 clusters experience little of no dissolution between ~10 and ~200 Myr, while Class 3 clusters experience a strong number evolution during the same time period.



When modeled with Schechter functions, Class 1+2 clusters are consistent with a ~30x mode massive cut-off than Class 3 clusters

Adamo+2016

Conclusions

(Actually: SPECULATIONS)

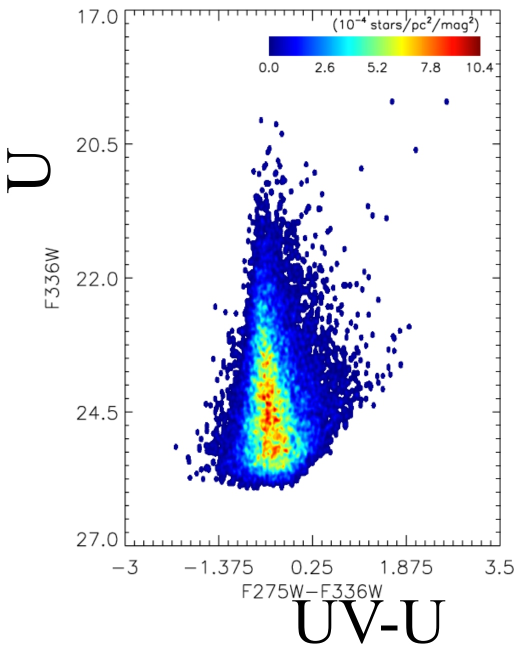
- Class 3 systems are possibly short-lived `associations', ~a few tens Myr.
- If systems of all three classes are born at gas density peaks the preferential dissolution of class 3 may explain the weaker clustering of class 1+2.
- The lifespan of class 3 systems is consistent with the age of the stars in the interarm regions of M101, > 40 Myr (Crocker et al. 2015).
- Also consistent with the randomization timescale of stellar populations in NGC6503, around 60 Myr (Gouliermis et al. 2015).
- Star clusters travel significantly from their birth-sites over the span of ~40-50 Myr, and randomize though the galaxy.
- Tension with simulations of spirals, where arms can last for 100' of Myr (Dobbs et al. 2016).

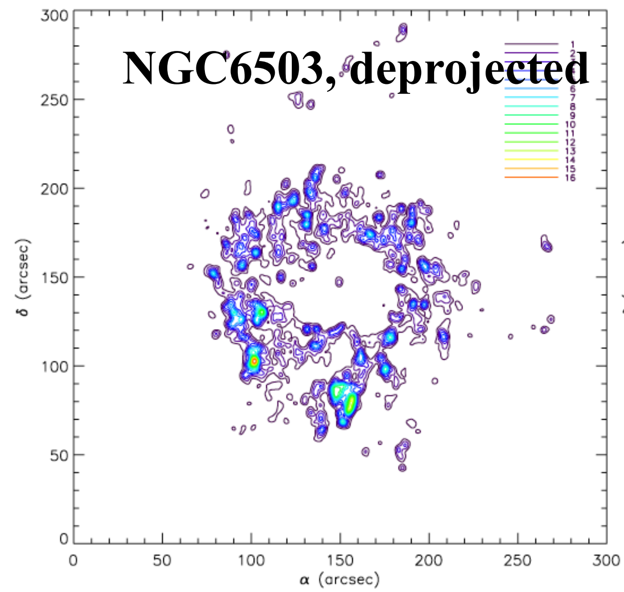
A fraction of the stars in the field originate from dissolving star systems over a few tens Myr. If numbers work out correctly, this could imply a single (hierarchical) mode of star formation and a universal IMF. **(check near-future results from Michele and Greg for this)**

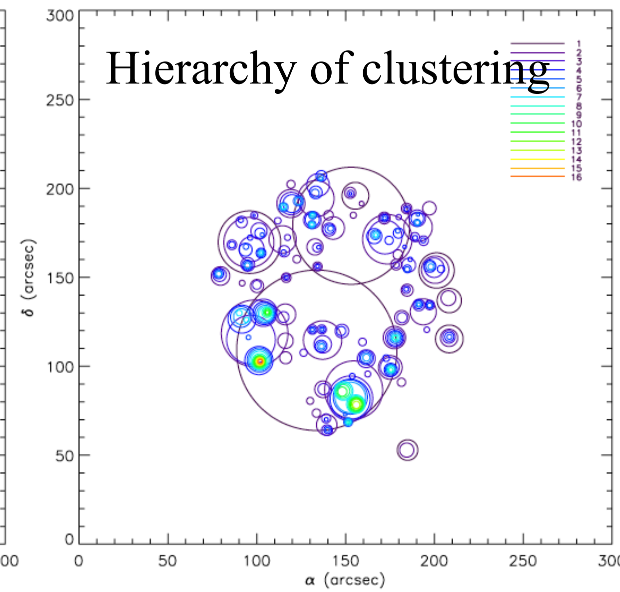
STAY TUNED

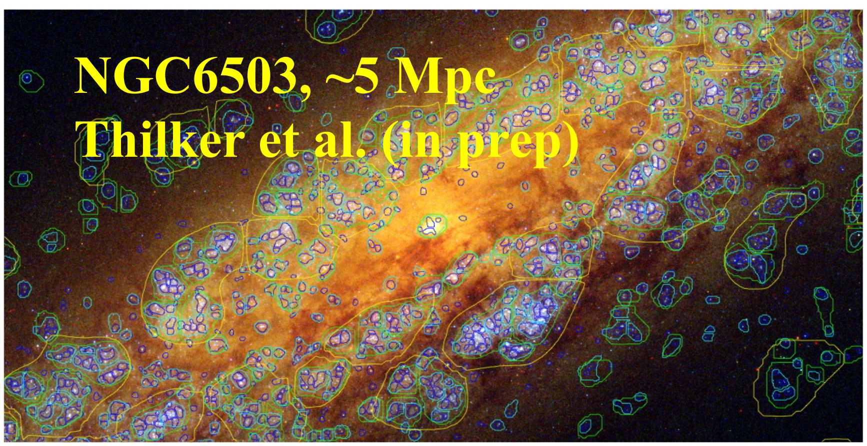
Clustering of Stars

Gouliermis+2015, MNRAS









- Structure sizes ~130 pc (similar to MagClouds)
- Structures dispersion ~60 Myr (shorter than MagClouds)
- ~40% of young stars are not part of structures